CDF note 6389

Search for Anomalous Production of Diphoton + Missing Transverse Energy Events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV and Limits on Gauge Mediated Supersymmetry Breaking Models

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: July 31, 2004)

We present the results of a search for anomalous production of diphoton events with large missing transverse energy in 202 ± 12 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the Collider Detector at Fermilab. We observe no events with an expected Standard Model background of $0.27 \pm 0.07(\mathrm{stat}) \pm 0.10(\mathrm{sys})$ events. The results are interpreted in terms of a gauge–mediated supersymmetry–breaking scenario in which the branching ratio for $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G} \approx 100\%$. The results exclude models with a $\tilde{\chi}_1^{\pm}$ mass less than 167 GeV/c^2.

Preliminary Results for Winter 2003 Conferences

I. INTRODUCTION

The standard model (SM) has been enormously successful, but is incomplete. For theoretical reasons [1, 2], and because of the '$ee\gamma\gamma\not\!\!E_T$' candidate event recorded by the CDF Detector in Run I [3], there are compelling reasons to search in high–energy proton anti-proton collisions for the production of heavy new particles that decay producing the signature of $\gamma\gamma$+missing transverse energy ($\not\!\!E_T$). Of particular theoretical interest are supersymmetric (SUSY) models with gauge–mediated SUSY–breaking (GMSB), that are characterized by a SUSY–breaking scale Λ as low as 100 TeV [1]. In these models, a light gravitino, $\tilde{G}$, is the lightest SUSY particle, weakly interacting and stable, and the lightest neutralino, $\tilde{\chi}_1^0$, decays through $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, with a branching ratio of nearly 100% if it is the next–to–lightest SUSY particle (NLSP). Pair production and decay of SUSY particles will result in two $\tilde{\chi}_1^0$'s, which cascade to a final state of $\gamma\gamma + \not\!\!E_T + X$, where X represents any other particles.

In this paper we summarize a systematic search [4] for anomalous production of inclusive $\gamma\gamma + \not\!\!E_T + X$ events in 202 ± 12 pb^{-1} [5] of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the CDF II detector. We examine events with two isolated, central ($|\eta| \lesssim 1.0$) photons with $E_T > 13$ GeV for the presence of anomalous $\not\!\!E_T$. This work updates a previous search for SUSY in this channel from CDF [3] by using an improved detector, a larger dataset, and a reoptimized search strategy, and is complementary to similar searches performed elsewhere [6].

The CDF detector is described in detail in [7].

II. DATA SAMPLE & EVENT SELECTION

We select candidate events using both online (during data taking) and offline selection requirements. Online, events are selected for the presence of two photon candidates, identified by the three-level trigger as two isolated electromagnetic clusters [8] with $E_T > 12$ GeV, or two electromagnetic clusters with $E_T > 18$ GeV and no isolation requirement.

The offline diphoton event selection requires two central (approximately $0.05 < |\eta| < 1.0$) electromagnetic clusters satisfying: a) $E_T > 13$ GeV (where the 12 GeV trigger becomes $> 99.7\%$ efficient), b) not near the boundary in ϕ of a calorimeter tower [10]; c) the ratio of hadronic to electromagnetic energy, Had/EM, $< 0.055 + 0.00045E^{\gamma}$ (to remove jets); d) no tracks, or only one track with $p_T < 1$ GeV/c, extrapolating to the towers of the cluster, (to remove electrons or jets); e) isolated in the calorimeter and tracking chamber [9] (to remove jets) f) a shower shape in the CES consistent with a single photon (to remove π^0 backgrounds); g) no other photon candidate within the same 15^0 segment in ϕ of the CES (to remove π^0 backgrounds); and h) $|z_{\mathrm{vertex}}| < 60$ cm (to maintain the projective geometry of the calorimeter).

To minimize the number of events with large fake $\not\!\!E_T$, we correct for jet energy loss in cracks between detector components and for nonlinear calorimeter response [13]. To avoid cases where a jet is mis-measured by the calorimeter, we remove events which have a jet with uncorrected $E_T > 10$ GeV pointing within 10 degrees in azimuth of the $\not\!\!E_T$ direction, or the direction opposite to the $\not\!\!E_T$. To reduce beam–related or cosmic–ray backgrounds, we reject events with significant energy out-of-time with the collision [11]. An event is also rejected if there are unattached hits in the muon chamber within 30 degrees of the photon or if there is a pattern of energy in the calorimeter indicative of beam–related backgrounds [12], but only in the case that the $\not\!\!E_T$ is equal in magnitude and opposite in direction to a photon, or to the vector sum of the momenta of two photons which are nearby in ϕ (a signature of a beam-related background). After these cuts, and before the final $\not\!\!E_T > 45$ GeV requirement, this diphoton candidate sample consists of 3,306 events.

III. BACKGROUNDS

The dominant backgrounds are: QCD interactions with $\gamma\gamma$, γj, and jj final states (where j represents a jet), in which one or more jets "fakes" a photon and the $\not\!\!E_T$ results from mismeasurement of the energy balance in the detector; inclusive '$e\gamma$' production, in which an electron from a W or Z decay fakes a photon and the $\not\!\!E_T$ is either real or fake; and events with energy from beam-related backgrounds or cosmic rays hitting the detector coincident with a $p\bar{p}$ collision.

A. QCD Backgrounds

Virtually all of the events in the diphoton candidate sample are QCD interactions producing combinations of photons and jets faking photons. Standard techniques [8] can be used to estimate the individual contributions to be 47 ± 6% γj, 29 ± 4% $\gamma\gamma$, and 24 ± 4% jj production. To estimate the shape of the $\not\!\!E_T$ distribution of this background, we use a diphoton control sample of 7,806 events selected by requiring two clusters that pass most, but not all, of the diphoton candidate sample requirements. Specifically, the control sample events must pass the same photon E_T, z_{vertex}, fiducial, $\Delta\phi(\not\!\!E_T\text{-}jet)$, beam–related and cosmic–ray background cuts, but satisfy the following photon identification and isolation requirements: a) calorimeter isolation 50% looser than for the signal selection; b) tracking isolation < 5 GeV/c; c) Had/EM < 0.125; d) no tracks, or only one track with $p_T < 0.25\ E_T/c$. If an event passes the signal region cuts, it is rejected from the control sample. We expect this sample, after a subtraction of $e\gamma$ events which contain real $\not\!\!E_T$ production, to have a similar calorimetric response and resolution to those of the diphoton candidate sample. We observe there to be a small difference in the sum of all the energy in the event (ΣE_T) and since the $\not\!\!E_T$ resolution is a function of the ΣE_T, we correct the $\not\!\!E_T$ in the control sample for this difference [14]. To predict the number of events with large $\not\!\!E_T$, we normalize the corrected control sample distribution to the number of diphoton candidate events in the region $\not\!\!E_T < 20$ GeV, and fit with a double exponential to derive a prediction at large $\not\!\!E_T$. We predict $0.01 \pm 0.01(\text{stat}) \pm 0.01(\text{sys})$ events with $\not\!\!E_T > 45$ GeV, where the uncertainty is dominated by differences in the prediction using various control sample selection requirements, the choice of fit function, and the statistical uncertainties of the sample.

B. $e\gamma$ Backgrounds

Events with real electrons ($W\gamma \to e\nu\gamma$, $Z\gamma \to ee\gamma$) can contribute to the background when the electron track is lost (by tracking inefficiency or bremsstrahlung of most of its energy) to create a fake photon and, for W decays, real $\not\!\!E_T$ can come from the neutrinos. We begin to estimate this background by selecting $e\gamma$ events in the data. The diphoton triggers do not reject electromagnetic clusters with tracks, so they are efficient for these events. We find 462 $e\gamma$ events. Secondly, examining a $Z \to ee$ sample, we estimate $1.0 \pm 0.4\%$ of electrons will pass the diphoton candidate sample requirements, including charged track rejection. Lastly, we multiply the number of the observed $e\gamma$ events by the rate at which electrons will fake photons. From this source, we expect $0.14 \pm 0.06(\text{stat}) \pm 0.05(\text{sys})$ background events in the sample with $\not\!\!E_T >$ 45 GeV. The uncertainty is dominated by the statistical uncertainty in the fake rate and the uncertainty in the purity of the $e\gamma$ sample

C. Non-Collision Backgrounds

Beam–related sources, cosmic rays and other non–collision interactions can contribute to the background by producing one or more spurious photon candidates and real $\not\!\!E_T$, if they overlap with a SM event. While the rate at which these events contribute to the diphoton candidate sample is low, most contain large $\not\!\!E_T$. The dominant contribution comes from sources which produce two spurious photons at once, such as a cosmic muon undergoing bremsstrahlung twice. This background is estimated from the data using a sample of events with no primary collision and two electromagnetic clusters, multiplied by the rate at which clusters from cosmic rays pass the diphoton candidate sample requirements. Backgrounds in which only one of the photons, or only the $\not\!\!E_T$, is from a non-collision source are estimated to be very small. The total of number of events from non–collision sources in the $\not\!\!E_T > 45$ GeV sample is expected to be $0.12 \pm 0.03(\text{stat}) \pm 0.09(\text{sys})$. The uncertainty includes the uncertainty in the rate at which spurious clusters pass diphoton candidate sample cuts and the statistics and purity of the sample with no primary collision.

IV. PRELIMINARY RESULTS

In Section III we discussed the dominant SM backgrounds to the diphoton sample and estimated the event counts from each background source. We expect a total of $0.27 \pm 0.07 \pm 0.10$ events with $\not\!\!E_T > 45$ GeV. Table I summarizes the backgrounds for four different $\not\!\!E_T$ requirements and compares with the observed numbers of events. Each is consistent with the expectations from the background predictions within errors.

$\not\!\!E_T$ Cut	QCD	$e\gamma$	Non-Collision	Total	Observed
25 GeV	$4.01^{+4.13}_{-2.06} \pm 3.76$	$1.40 \pm 0.52 \pm 0.45$	$0.54 \pm 0.06 \pm 0.42$	$5.95^{+4.16}_{-2.13} \pm 3.81$	3
35 GeV	$0.30^{+0.23}_{-0.12} \pm 0.22$	$0.84 \pm 0.32 \pm 0.27$	$0.25 \pm 0.04 \pm 0.19$	$1.39^{+0.39}_{-0.34} \pm 0.40$	2
45 GeV	$0.01 \pm 0.01 \pm 0.01$	$0.14 \pm 0.06 \pm 0.05$	$0.12 \pm 0.03 \pm 0.09$	$0.27 \pm 0.07 \pm 0.10$	0
55 GeV	$0.00 \pm 0.00 \pm 0.00$	$0.05 \pm 0.03 \pm 0.02$	$0.07 \pm 0.02 \pm 0.05$	$0.12 \pm 0.04 \pm 0.05$	0

TABLE I: Number of observed and expected events from the background sources as a function of the $\not\!\!E_T$ requirement. Here QCD includes $\gamma\gamma, \gamma j$ and jj. The errors are statistical first then systematic.

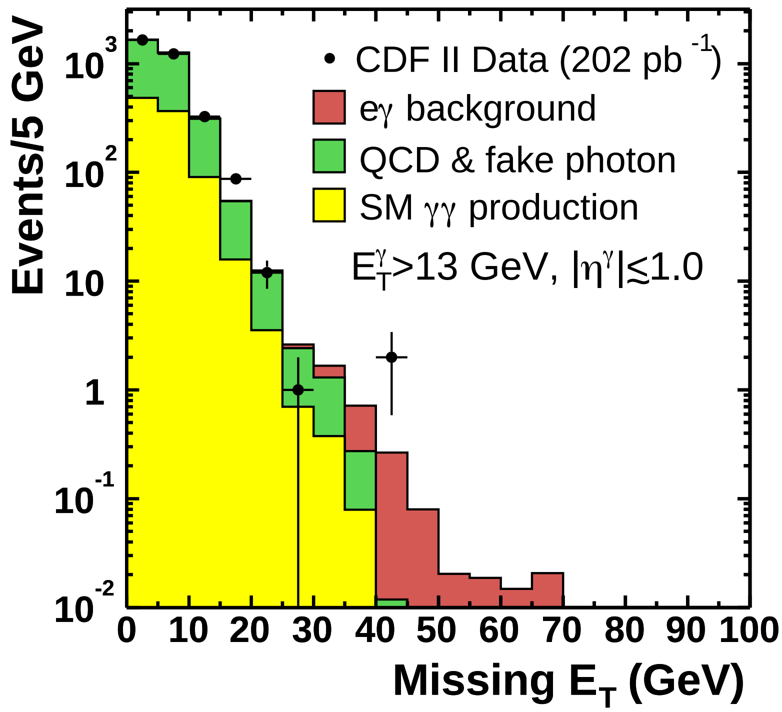

FIG. 1: he $\not\!\!E_T$ spectrum for events with two isolated central photons with $E_T > 13$ GeV and $|\eta| < 1.1$. The data is in good agreement with the background predictions. There are no events above the $\not\!\!E_T > 45$ GeV threshold.

Fig. 1 shows the $\not\!\!E_T$ distribution for the diphoton sample with $E_T^{\gamma} > 13$ GeV along with the background predictions from sum of QCD + fake $\not\!\!E_T$ and $e\gamma$ production. Note that for completeness we have separated out the contribution from the QCD diphoton production (using CES/CPR background subtraction) even though those numbers are not used in the analysis. The data is in good agreement with the background predictions. There are no events above the $\not\!\!E_T > 45$ GeV threshold.

V. MONTE CARLO SIMULATION OF SUSY

Since there is no evidence for events with anomalous $\not\!\!E_T$ in our diphoton candidate sample, we set limits on new particle production from GMSB using the parameters suggested in Ref. [15], and requiring the $\tilde{\chi}_1^0$ to be the NLSP. In this scenario, $\gamma\gamma+\not\!\!E_T$ event production is dominated by $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ production and decay. Only negligibly short $\tilde{\chi}_1^0$ lifetimes are considered. To estimate the acceptance for this scenario we generate GMSB events using ISAJET [16] with CTEQ5L parton distribution functions [17]. The production cross sections from ISAJET are corrected by a K-factor of approximately 1.2 to match the next-to-leading order (NLO) prediction [20]. We process the events through the GEANT-based [18] detector simulation, and correct the resulting efficiency with information from data measurements, when possible.

By ignoring the electron's track in $Z \to ee$ events, we can create a control sample of electromagnetic showers. We estimate that an isolated photon hitting the fiducial portion of the detector has a 77% probability of passing the identification and isolation criteria. However, since the isolation[9] of the photons is predicted from the Monte Carlo to be a strong function of the mass of the SUSY scale, we find the signal efficiency to be 61%. For the $\not\!\!E_T > 45$ GeV requirement, the fraction of generated signal events that pass all cuts rises linearly from 3.5% at $M_{\tilde{\chi}_1^{\pm}}$=100 GeV/c^2 to approximately 8% at 180 GeV/c^2 and remains roughly flat for larger masses due to the inefficiency of the $\Delta\phi(\not\!\!E_T - j)$ cuts offsetting the additional acceptance due to kinematic factors. The relative systematic uncertainty in the efficiency of the photon identification and isolation requirements is $\approx 6.5\%$ per photon. Other significant uncertainties in the Monte Carlo model predictions are from the initial/final state radiation (10%), Q^2 of the interaction (3%) and uncertainty in parton distribution functions ($^{+1}_{-5}$%). Combining these numbers gives a total 18% relative systematic uncertainty.

VI. OPTIMIZATION AND FINAL RESULTS

The cuts defining the final data sample were determined by a study to optimize the statistically–unbiased *expected limit*, putting aside, the signal region data. To compute the expected 95% confidence level (C.L.) cross section upper limit, we combined the predicted signal and background, an 18% systematic uncertainty, and a Bayesian limit calculation with a flat prior into the the prescription of Ref. [19]. The expected limits were computed as a function of $\not\!\!E_T$, photon E_T, and $\Delta\phi(\not\!\!E_T - j)$ cuts, and we found that the best limit is predicted with the selection described above for the diphoton candidate sample, and $\not\!\!E_T > 45$ GeV. The statistical analysis indicates that the most probable expected result would be an exclusion of $M_{\tilde{\chi}_1^\pm}$ less than 161 GeV/c^2.

In the data signal region, with $\not\!\!E_T > 45$ GeV, we observe zero events and set the 95% C.L. upper limit of 3.3 signal events. Figure 2 shows the observed cross section limits as a function of $M_{\tilde{\chi}_1^\pm}$ along with the theoretical LO and NLO production cross sections. Using the NLO predictions we set a limit of $\mathrm{M}_{\tilde{\chi}_1^\pm} > 167$ GeV/c^2. From mass relations in the model, we equivalently exclude $\mathrm{M}_{\tilde{\chi}_1^0} < 93$ GeV/c^2 and $\Lambda < 69$ TeV.

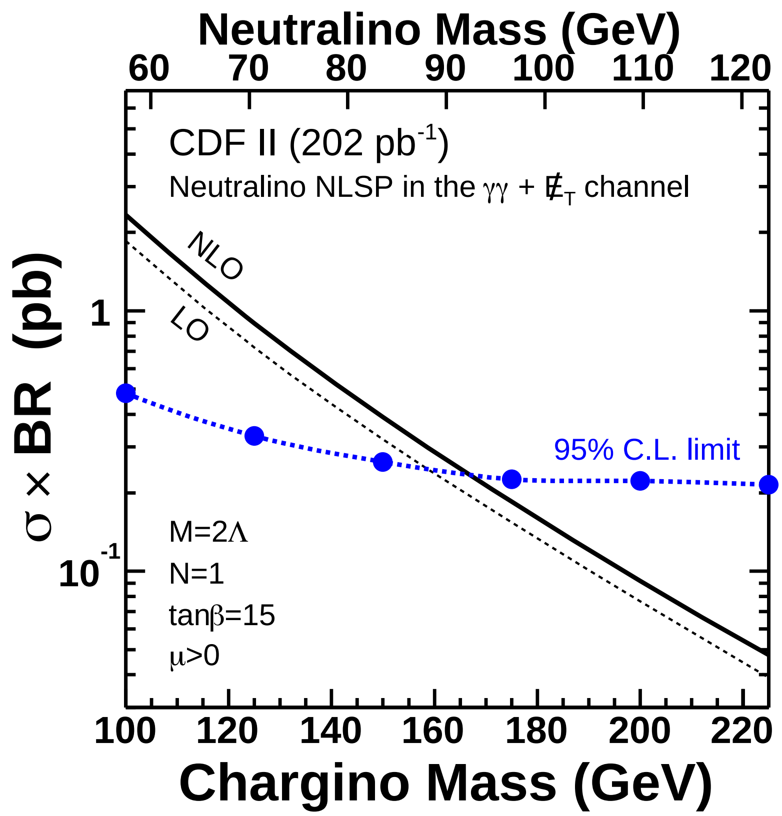

FIG. 2: The 95% C.L. upper limits on the total production cross section times branching ratio versus $M_{\tilde{\chi}_1^\pm}$ and $\mathrm{M}_{\tilde{\chi}_1^0}$ for the light gravitino scenario using the parameters proposed in Ref. [15]. The lines show the experimental limit and the LO and NLO theoretically predicted cross sections. We set a limit of $\mathrm{M}_{\tilde{\chi}_1^\pm} > 167$ GeV/c^2 at 95% C.L..

VII. CONCLUSIONS

In conclusion, we have searched 202 pb^{-1} of inclusive diphoton events for anomalous production of missing transverse energy as evidence of new physics. We find good agreement with standard model expectations and have interpreted our results in terms of a GMSB scenario and excluded models with the lightest chargino masses less than 167 GeV/c^2 at 95% C.L.

ACKNOWLEDGMENTS

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

---

[1] S. Dimopoulos, S. Thomas, J. D. Wells, Nucl. Phys. B **488**, 39 (1997); S. Ambrosanio, G.D. Kribs and S.P. Martin, Phys. Rev. D **56**, 1761 (1997); G. F. Giudice and R. Rattazzi, Phys. Rept. **322**, 419 (1999); and S. Ambrosanio, G. Kane, G. Kribs, S. Martin and S. Mrenna, *Phys. Rev.* D **55**, 1372 (1997).

[2] R. Culbertson *et al.*, hep-ph/0008070

[3] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **81**, 1791 (1998); CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **59**, 092002 (1999).

[4] M. S. Kim, Ph.D thesis, Kyungpook National University, 2004.

[5] D. Acosta *et al.*, Nucl. Instrum. Meth. A **494**, 57 (2002)

[6] DØ Collaboration, S. Abachi *et al.*, *Phys. Rev. Lett.* **78**, 2070 (1997); ALEPH Collaboration, A, Heister *et al.*, Eur. Phys. J. **C25** 339 (2002); L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. B **472**, 420 (2000); OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C18** 253 (2000); DELPHI Collaboration, P. Abreu *et al.*, Eur. Phys. J. **C17** 53 (2000).

[7] CDF II Collaboration, R. Blair *et al.*, FERMILAB-PUB-96/390-E (1996).

[8] See F. Abe *et al.*, *Phys. Rev.* D **52**, 4784 (1995) for a detailed description of the definition of an electromagnetic cluster and *Phys. Rev. Lett.* **73**, 2662 (1994) for a description of photon identification and the purity estimation methods.

[9] To reject hadronic backgrounds which fake prompt photons, candidates are required to be isolated in the calorimeter and tracking chamber. In the calorimeter the isolation is defined as the energy in a cone of 0.4 in $\eta-\phi$ space, minus the photon cluster energy, and corrected for energy loss into cracks as well as the number of vertices in the event. We require isolation $< 0.1 \times E_T$ for E_T <20, and < 2.0 GeV+0.02 $\times$ ($E_T - 20$ GeV) above. In the tracking chamber we require the scalar sum of the p_T of all tracks in the 0.4 cone to be < 2.0 GeV+0.005 $\times$ E_T.

[10] The fiducial region is defined to be 0.05$< |\eta| < 1.0$ and 0$< \phi < 2\pi$ with ∼87% coverage.

[11] Only the central hadronic calorimeter has timing information associated with the energy deposited. For this dataset, we require all towers with at least 0.5 GeV of energy to be within 3σ of their expected time of arrival.

[12] M. Unel and R. Tesarek, Nucl.Instrum.Meth. A506 7, 2003.

[13] See F. Abe *et al.*, *Phys. Rev.* D **45**, 1448 (1992) for a description of the jet-finding algorithm and the jet energy corrections. Jets are reconstructed here with a cone in $\eta - \phi$ space of radius 0.4.

[14] The means of the ΣE_T distributions for the two samples are separated by approximately 6%, most likely due to differences in the underlying event and Q^2 of the samples as they have different percentage contributions from $\gamma\gamma, \gamma j$ and jj. The correction is done by taking the expected shape of the $\not\!\!E_T$ distribution from the control sample as a function of ΣE_T, and normalizing to the observed ΣE_T distribution in the signal sample.

[15] B. C. Allanach *et al.*, Eur. Phys. J. **C25** 113 (2002). We take the messenger mass scale $M_{\rm M} = 2\Lambda$, $\tan(\beta) = 15$, $\mathrm{sgn}(\mu) = 1$ and the number of messenger fields $N_{\rm M} = 1$.

[16] H. Baer, F. E. Paige, S. D. Protopopescu and X. Tata, hep-ph/0001086.

[17] H. L. Lai *et al.*, Eur. Phys. J. **C12** 375 (2000).

[18] R. Brun *et al.*, CERN-DD/EE/84-1 (1987).

[19] E. Boos, A. Vologdin, D. Toback and J. Gaspard, *Phys. Rev.* D **66**, 013011 (2002).

[20] The K-factor has a small dependence on the $\tilde{\chi}_1^\pm$ mass and is taken from W. Beenakker *et al.*, *Phys. Rev. Lett.* **83**, 3780 (1999) and T. Plehn (private communication).